



Spatial-temporal change of carbon storage and sink of wetland ecosystem in arid regions, Ningxia Plain

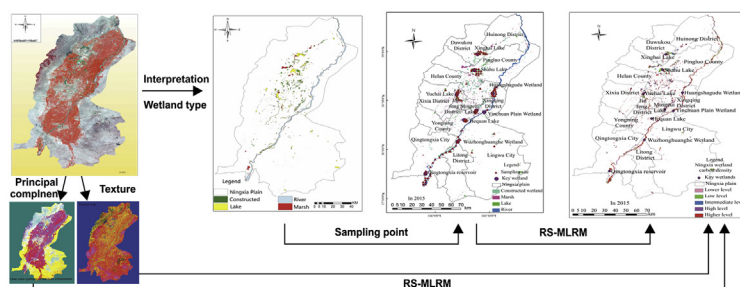
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GRAPHICAL ABSTRACT



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ABSTRACT

Accurate assessment of wetland ecosystem carbon sinks is an estimation of future atmospheric CO₂ concentrations, prediction of climate change and its impact on wetland ecosystems. In this study, using remote sensing data and 351 wetland sample sites in 2015, a remote sensing multiple linear regression model (RS-MLRM) was constructed to clarify the carbon storage capacity and its changing process from 2000 to 2015 and their controlling factors in arid regions wetlands. The results are as follows: (1) The studied wetlands acted as atmospheric carbon sinks from 2000 to 2015, increasing by 3.88×10^4 tC/a. Moreover, the soil carbon sink (0–40 cm) was approximately twice that of the vegetation carbon sink. (2) Carbon sinks had a clear spatial distribution, with high concentrations in Helan and Pingluo Counties in the central Ningxia Plain. From 2005 to 2015, constructed wetlands significantly increased the carbon sink ($P < 0.05$) and were the main contributors to carbon sequestration, indicating that positive human intervention enhances the carbon sink effect of wetlands. (3) Human activities, policy factors, soil physical and chemical properties and nutrients were the main factors affecting carbon sink in Ningxia Plain Wetland in arid regions. (4) The results provides a scientific basis for the protection and management of wetland ecosystems in arid areas.

1. Introduction

Since the 1970s, increasing global CO₂ concentrations have received substantial attention from governments and researchers globally (Suo

et al., 2010; Zhang et al., 2013), mostly notably related to the circulation and distribution of carbon. Such research has predominantly been focused on finding methods of collecting and fixing carbon emitted through energy consumption in soils and vegetation (Bernal

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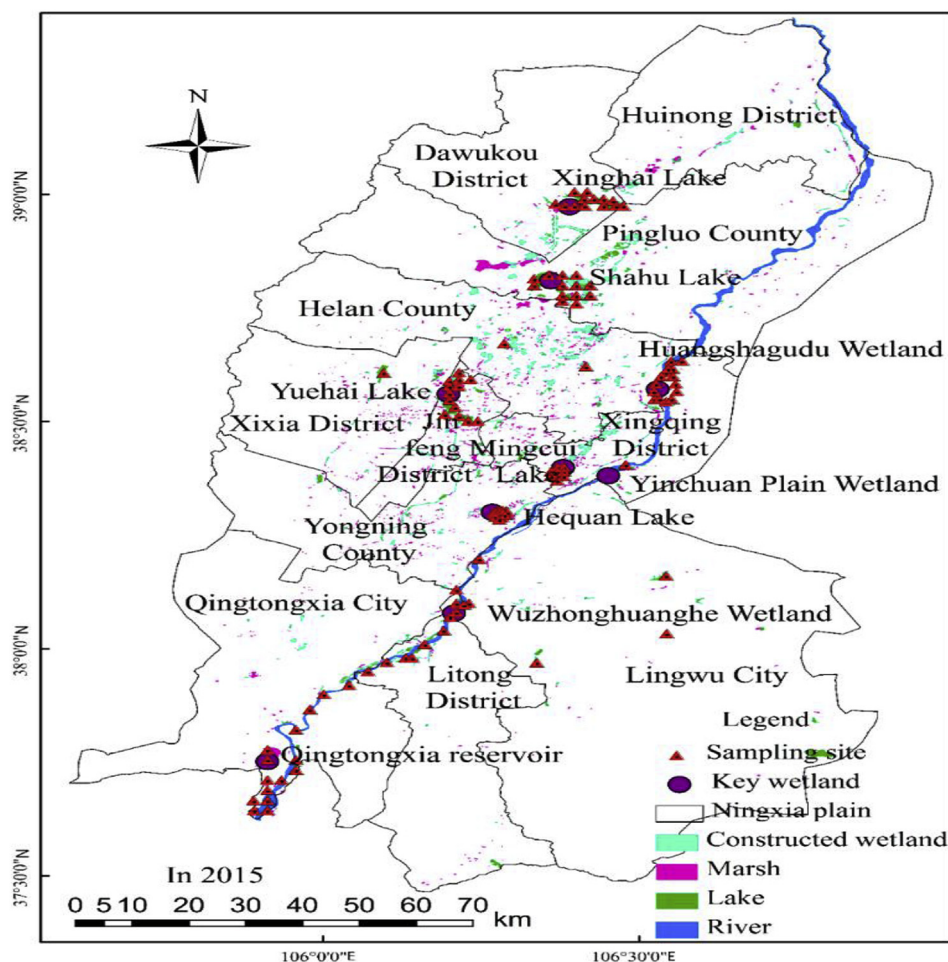


Fig. 1. Wetland distribution in the Ningxia Plain.

and Mitsch, 2008; Pan et al., 2010). Therefore, the carbon sink of wetlands is of significant academic interest because wetland ecosystems help balance carbon-bearing greenhouse gases in the atmosphere (Xu et al., 2011; Mi et al., 2013).

Even though wetlands account for only 4–6% of the Earth's land area (Grasset et al., 2017; Strachan et al., 2015; Junk et al., 2013; Aselmann and Crutzen, 1989; Matthews and Fung, 1987), their carbon storage capacity accounts for 20–30% of the terrestrial ecosystem carbon storage (Carnell et al., 2018; Mitsch et al., 2013; Zeng et al., 2013). Wetland ecosystems are an important component in the atmospheric interactions of the global carbon cycle (Lee et al., 2015; Meng et al., 2016), but are sensitive to climate variability, particularly in the context of global climate change (Cao et al., 2017; Zhang et al., 2013; Sulman et al., 2009).

As an important part of the arid areas in the northwest, studying the carbon sink is of great significance for understanding the global carbon cycle. However, there are currently few studies on the wetland carbon sink in arid areas. Currently, research on wetland carbon mainly focuses on soil organic and its distribution characteristics in arid areas wetland (Zhang, 2007, 2011; Mi et al., 2013; Dong et al., 2015). These studies have important demonstration and exploration for the study of carbon dynamics. However, the wetland carbon storage and carbon sinks and their changes are still unclear. The research methods and contents are relatively simple. In particular, comprehensive assessment of wetland carbon stocks and carbon sink are lack of integration of new technologies and methods in arid wetlands (Cui et al., 2012; Zhuang et al., 2015). A combination of “3S” (global positioning system, GPS; geographic information system, GIS; RS) technology and sample data can

be used to estimate organic carbon on small to large spatial scales (Cui et al., 2012). Li Shuang et al. used the remote sensing factor to construct a vegetation biomass inversion model, which inverts the biomass of the current (in 2008) and historical years (in 2006 and in 2004), and achieved good results (Li, 2013).

The Ningxia Plain is located in the arid area of Northwest China, and its ecological environment is particularly vulnerable to climate change. Arid wetlands cover 157,700 hm^2 , accounting for 76.27% of the total wetland area in Ningxia, and have origins and characteristics distinct from those of wet area wetlands. They mainly rely on the Yellow River and its irrigation and drainage system for growth, and show clear seasonal and temporal variability in their distribution. These wetlands control flooding, pollution, and the microclimate, and play important roles in biodiversity and environmental protection. They are rare in desert and semi-desert regions, and have very close ecological relationships with the desert matrix (Mi et al., 2013). Most importantly, they are closely linked to human activities in terms of water conservation. Due to the influence of factors such as the return of irrigated farmland, the eutrophication of wetlands has become prominent. Existing studies have mainly focused on the amount estimation of carbon storage and carbon sink of regional ecosystem, but analysis of the change process on time scale and the spatial difference of changing trend is limited (Zhou et al., 2007; Dong et al., 2015; Bu et al., 2016; Zhu and Shao, 2018). The objective of this study is to develop a new approach that can overcome overcoming the time scale and the spatial difference limitation. The models are tested, and the performance evaluated, and can improve the accuracy of organic carbon estimation using a combination of spectral information, textural features,

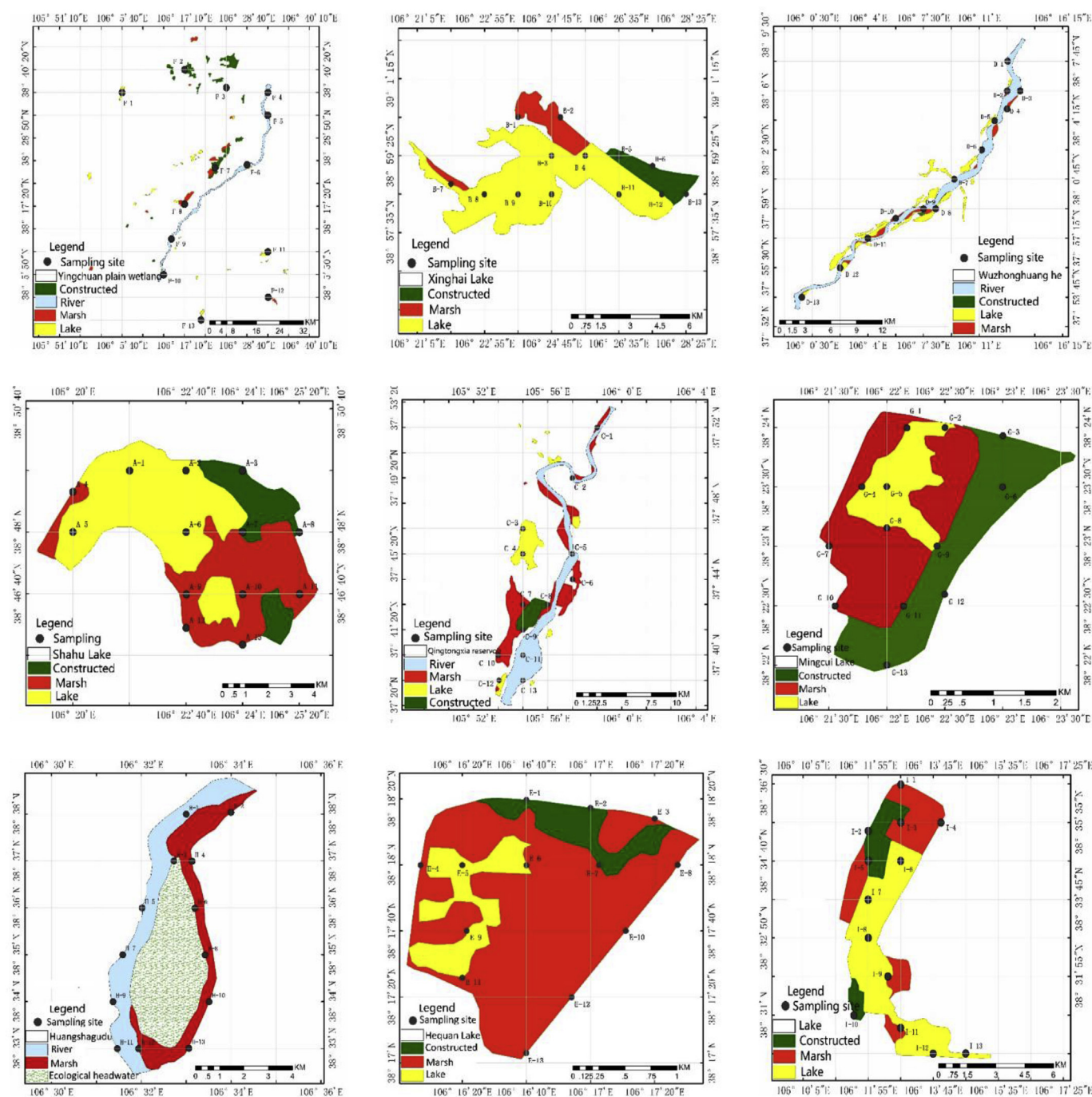


Fig. 2. Sampling sites for key wetlands in the Ningxia Plain in 2015.

vegetation indices, and measured data in the typical wetland. Meanwhile, the spatial and temporal variation characteristics of carbon sinks were analyzed using the models in the Ningxia Plain wetland from 2000 to 2015. In order to clarify the carbon storage capacity and its changing process in the region, it provides a scientific basis for the protection and management of wetland ecosystems in the region.

2. Materials and methods

2.1. Study area

The Ningxia Plain (105°5′–106°56′E and 37°46′–39°23′N) occupies the eastern part of Northwest China and is located in the upper reaches of the Yellow River and in the northern part of the Ningxia Hui

Autonomous Region. The cities of Yinchuan, Shizuishan, Wuzhong, and Qingtongxia are located along the coast of the Yellow River, with a combined area of 7790 km², accounting for 42.6% of the land area in Ningxia. The Yellow River runs from south to north through the Ningxia Plain, with canals and ditches providing convenient irrigation. The region has a continental temperate arid climate, with an average annual temperature of 9.0 °C and rainfall of 180–200 mm. The potential annual evaporation is 1825 mm, the average annual humidity is 55%, and the Palmer drought severity index is 7.8–8.0.

According to the classification standard for wetland types in China, the Ningxia Plain contains river, lake, marsh, and constructed wetlands. Soil types are mainly silt, alluvial, marsh, and saline-alkali soil and the vegetation includes mainly reeds and aquatic plants. Since 2002, the government of Ningxia Hui Autonomous Region has carried out a series

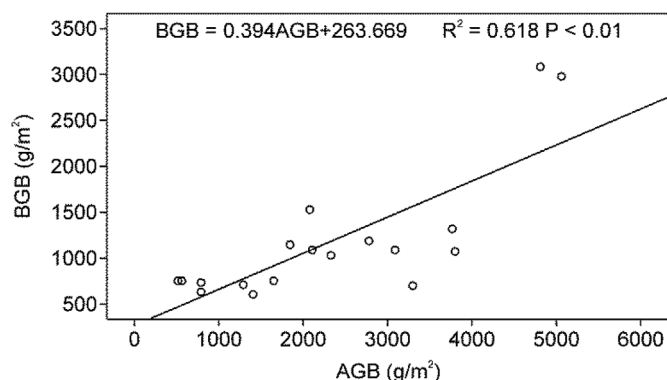


Fig. 3. Correlation of AGB and BGB in wetlands in the Ningxia Plain.

of wetland ecological restoration and protection projects, such as re-treating fields (ponds), returning water to lake, returning farmland to lake, and dredging. The wetland area has continuously grown, vegetation coverage has increased, and the wetland landscape has changed significantly.

2.2. Data acquisition

2.2.1. Image data sources and processing

Image data were acquired using thematic mapper (TM) images (resolution 30 m × 30 m) from July 17, 2000, July 18, 2005, and July 27, 2010, and using operational land imager (OLI) images from July 28, 2015. Four images were obtained from the International Scientific Data Mirror website of the Computer Network Information Center of the Chinese Academy of Sciences (<http://www.gscloud.cn>). Images were chosen during the wet season to ensure comparability. The images were geometrically corrected, spliced, mosaicked, fused, enhanced, radiated, and corrected for atmospheric noise, using ERDAS software from Hexagon Geospatial (Wei and Tang, 2017) and had a corrected error of 0.5 pixels. Then, the OLI-2, -3, and -4 bands and the TM-3, -4, and -5 bands were selected because these bands have been shown to have the highest correlation with organic carbon (Song et al., 2015). The RS images were manually visualized for the study area using the software packages ENVI 4.7 and ArcGIS 10.0 to incorporate topography, hydrology, and wetland locations in the Ningxia Plain. Wetland locations in 2000, 2005, 2010, and 2015 were determined from GPS field survey data and interpretation marks using artificial extraction, which is more accurate than automatic extraction.

2.2.2. Sampling and analysis

Using the OLI-8 image for 2015, nine representative wetlands were selected as sampling sites in the study area. Sampling was performed in the National Wetland Park and the National Wetland Nature Reserve in the Ningxia Plain. To improve inversion model accuracy, sampling points must be evenly distributed throughout the wetland areas. To determine the sample distribution, a handheld GPS device (Grouth Bao A8, Grouth Ba China) was used to record the center of each wetland using latitude and longitude coordinates. Thirteen representative sample areas were selected within each of the nine key wetlands using a

Table 2

AGB and BGB carbon content average in the Ningxia Plain wetland.

Wetland type	Sample (A)	AGB carbon content g/kg	BGB carbon content g/kg	Equation
River	54	0.421	0.384	0.57AGB + 101.24
Lake	69	0.419	0.361	0.56AGB + 95.18
Marsh	86	0.413	0.374	0.56AGB + 98.61
Constructed wetland	54	0.417	0.387	0.57AGB + 102.04
Ningxia Plain wetland	264	0.418	0.378	0.56AGB + 97.03

grid selection method, so that 117 sample areas were identified. Three sample squares (1 × 1 m) were then randomly selected in each sample area, resulting in 351 sample sites, composed of 75 river, 93 lake, 111 marsh, and 72 constructed wetland sample sites (Figs. 1 and 2). The dominant vegetation types were cattails and reeds, accounting for approximately 90% of the vegetative cover.

Plants were harvested at each sample site during the wet season in 2015, placed in marked polyethylene bags, sealed, and taken back to the laboratory. All samples were dried to constant weight (accuracy of 0.01) at 85 °C, ground, and sieved using 60 mesh. Vegetative organic carbon (VOC) was determined for each sample using an Elementar vario MACRO CNS Elemental Analyzer (Germany) at a calcination temperature of 960 °C. Measurements from the three sample sites within each sample area were averaged for each value.

Three replicate spots were selected within the sampling quadrats based on collected vegetation samples, according to the concentration of the distribution of fabric roots in the study area (Lu et al., 2006) and referring to the method of stratified sampling of wetlands in the arid area (Wang and Jiao, 2016). In each sample, soil columns of 0–40 cm were collected using a cylindrical metal sampler (3 m in length and 5 cm in diameter). Each soil columns was divided into four layers (0–10, 10–20, 20–30, 30–40 cm) along the diagonal of the sample and drilled the soil, after which the same soil layers were evenly mixed, placed in a sealed and numbered sample bag, and sent back to the laboratory. Then, the samples were air-dried, passed through a 60-mesh sieve, sealed, and placed in a small refrigerator in the laboratory. At the same time, the ring knife method was used to take another four delamination cut soil column samples from each quadrat (Lv, 2005). These were placed into sealed bags for soil bulk density (BD) analysis. Each soil sample was analyzed for SOC and soil total nitrogen (STN), determined using the Elementar Vario MACRO analyzer. The soil total phosphorus (STP) content was determined using a UV-visible spectrophotometer (UV-2450, Shimadzu, Japan). Soil samples were oven-dried at 105 °C to constant weight so that the BD and water content could be determined from the mass change. Total salts were measured using a conductivity meter (DDS-307A, Rex Shanghai, China), and soil pH was measured using an acidity meter (PHB-5, Beijing Xin Yu Tengda Instrument Equipment Co. Ltd., Beijing, China) (Lv, 2005).

2.2.3. RS-MLRM

Multiple linear regression models were first proposed to solve economic problems by analyzing the relationship of selected independent variables to a dependent variable. The resulting empirical mathematical

Table 1

AGB biomass RS-MLRM and related statistics of wetlands in the Ningxia Plain.

Wetland type	Equation	R ²	P	Standard error (%)	Adjustment coefficient
River	0.195MSVI-5.183PC2-1597.88	0.903	0.001	9	0.891
Lake	5061.68RVI-12103.33NDVI + 2.33 ME -2.59PC2-4525.32	0.996	0.001	12	0.995
Marsh	5412.50RVI-14177.60NDVI + 2.98 ME -2.91PC2-4739.33	0.956	0.001	13	0.952
Constructed wetland	3818.28RVI-15584.97NDVI + 4.428 EN + 0.19DVI-4.49PC2- 2.72 ME-3861.66	0.994	0.001	10	0.992
Ningxia Plain wetland	5060.45RVI + 3.34 ME- 14473.70NDVI-4.72PC2- 3879.21	0.958	0.001	12	0.956

Table 3
Related statistics of RS-MLRM of soil organic carbon in the Ningxia Plain.

Wetland type	Equation	R ²	P	Standard error (%)	Adjustment coefficient
River	0.003AGB-27.786TM4 + 0.034	0.970	0.001	22	0.969
Lake	0.002AGB-0.936	0.941	0.001	15	0.937
Marsh	0.002AGB + 1.19	0.954	0.001	17	0.952
Constructed wetland	0.014AGB- 0.002PC2 + 3.26	0.982	0.001	19	0.979
Ningxia Plain wetland	0.002AGB + 0.69	0.973	0.001	23	0.972

Table 4
Evaluation of vegetation organic carbon RS-MLRM in the Ningxia Plain wetlands.

Wetland type	Measured (g/m ²)	Predicted (g/m ²)	RE (%)	RSME (g/m ²)
River	2698.79	2408.39	10.76	230.40
Marsh	3483.79	3201.66	8.10	172.13
Constructed wetland	3192.64	2908.05	8.91	204.59
Ningxia Plain wetland	2910.68	2631.15	9.60	219.53

Table 5
Evaluation of soil organic carbon RS-MLRM in the Ningxia Plain wetlands.

Wetland type	Measured (g/kg)	Predicted (g/kg)	RE (%)	RMSE (g/kg)
River	6.428	5.656	12.01	0.431
Lake	6.144	5.543	9.78	0.393
Marsh	8.126	7.361	9.41	0.325
Constructed wetland	7.143	6.73	5.78	0.301
Ningxia Plain wetland	6.952	6.134	11.77	0.379

formulae could then be used to predict values of a dependent variable when selected independent variables were known.

Let y be the dependent variable of mean AGB, while $(x_1, x_2, \dots, x_n)$ are the independent variables representing the RS factors. When the independent variables are a linear function of the dependent variable, the MLRM can be written as (Xu, 2011):

$$y = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n + \varepsilon \quad (1)$$

where a_0 is a constant term; $a_1, a_2, \dots, a_n$ are the regression coefficients; and ε is the random error. With a group of m samples, where x_{nm} is the observed value of x_n in the m th sample, a linear series of equations can be written as follows:

$$\begin{cases} y_1 = a_0 + a_1x_{11} + a_2x_{12} + \dots + a_nx_{1n} + \varepsilon \\ y_2 = a_0 + a_1x_{21} + a_2x_{22} + \dots + a_nx_{2n} + \varepsilon \\ \vdots \\ y_m = a_0 + a_1x_{m1} + a_2x_{m2} + \dots + a_nx_{mn} + \varepsilon \end{cases} \quad (2)$$

This series can be rewritten in matrix form as follows:

$$Y = AX + \varepsilon' \quad (3)$$

with Y, A, X , and ε' representing their corresponding matrices for the AGB values, coefficients, RS factors, and random error values, respectively.

Table 6
Soil organic carbon density RS-MLRM in the Ningxia Plain wetlands.

Wetland type	Sample (A)	Total nitrogen in soil (g/kg)	Soil bulk density (g/cm ³)	Equation
River	54	0.86	1.37	1.64AGB-15226.73TM4 + 16.44
Lake	69	1.06	1.39	0.85AGB - 396.86
Marsh	86	0.94	1.33	1.06AGB + 633.08
Constructed wetland	54	0.90	1.38	7.73AGB - 1.10PC2 + 1799.52
Ningxia Plain wetland	264	0.86	1.36	1.09AGB + 375.36

Based on the results of previous studies (Chen and Black, 1992; Gao et al., 2013; Song et al., 2011), 75% of the data was randomly selected (264 of 351 sampling points) from each wetland type in the Ningxia Plain. These data were then used to construct the biomass estimation model. The remaining 25% of the data (87 sampling points) was used to evaluate the accuracy of the biomass estimation model output. To test the fitting accuracy and prediction ability of the multiple linear regression model (RS-MLRM), the adjustment coefficients (R^2), root mean square errors (RMSE), precision system errors (SE), actual biomass (MB), and relative errors (RE%) were computed (Gao et al., 2013) using Eqs. (4)–(7):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (B_i - B'_i)^2} \quad (4)$$

$$SE = \sum_{i=1}^n \frac{|B_i - B'_i|}{n} \quad (5)$$

$$MB_i = \sum_{i=1}^n \bar{B}_i S_i \quad (6)$$

$$RE\% = 100\% \times \frac{|B_i - B'_i|}{B_i} \quad (7)$$

where B_i and B'_i represent the measured and predicted AGB values, respectively, for sample i ; $\bar{B}_i$ is the AGB per unit area averaged for the different vegetation types; and S_i is the vegetation cover area.

2.2.4. Wetland carbon sink measurement

The calculation for wetland organic carbon storage (WTOCS) (Schlesinger, 1997; Whittaker and Likens, 1975) is as follows:

$$WTOCS = A_1 \cdot VOC + A_2 \cdot SOCD \quad (8)$$

where A_1 is wetland vegetation cover area (hm²); A_2 is wetland ecosystem area (hm²); SOCD is wetland average soil carbon density (g/m²); VOC is wetland average vegetation carbon content (g/m²). WTOCS has the unit of tC. SOCD (g/m²) is calculated as follows:

$$SOCD = SOC \times H \times BD \quad (9)$$

where SOC is soil organic carbon content (g/kg); H is soil thickness (cm, taken here as 40 cm); and BD is soil bulk density (g/cm³).

Adopting the high-precision carbon sink measurement, which is preferred by the Intergovernmental Panel on Climate Change IPCC (2014) National Greenhouse Gas Inventory, we used a two-year average annual change to represent the change in a given carbon stock pool (known as the pool-difference approach) (Penman et al., 2003):

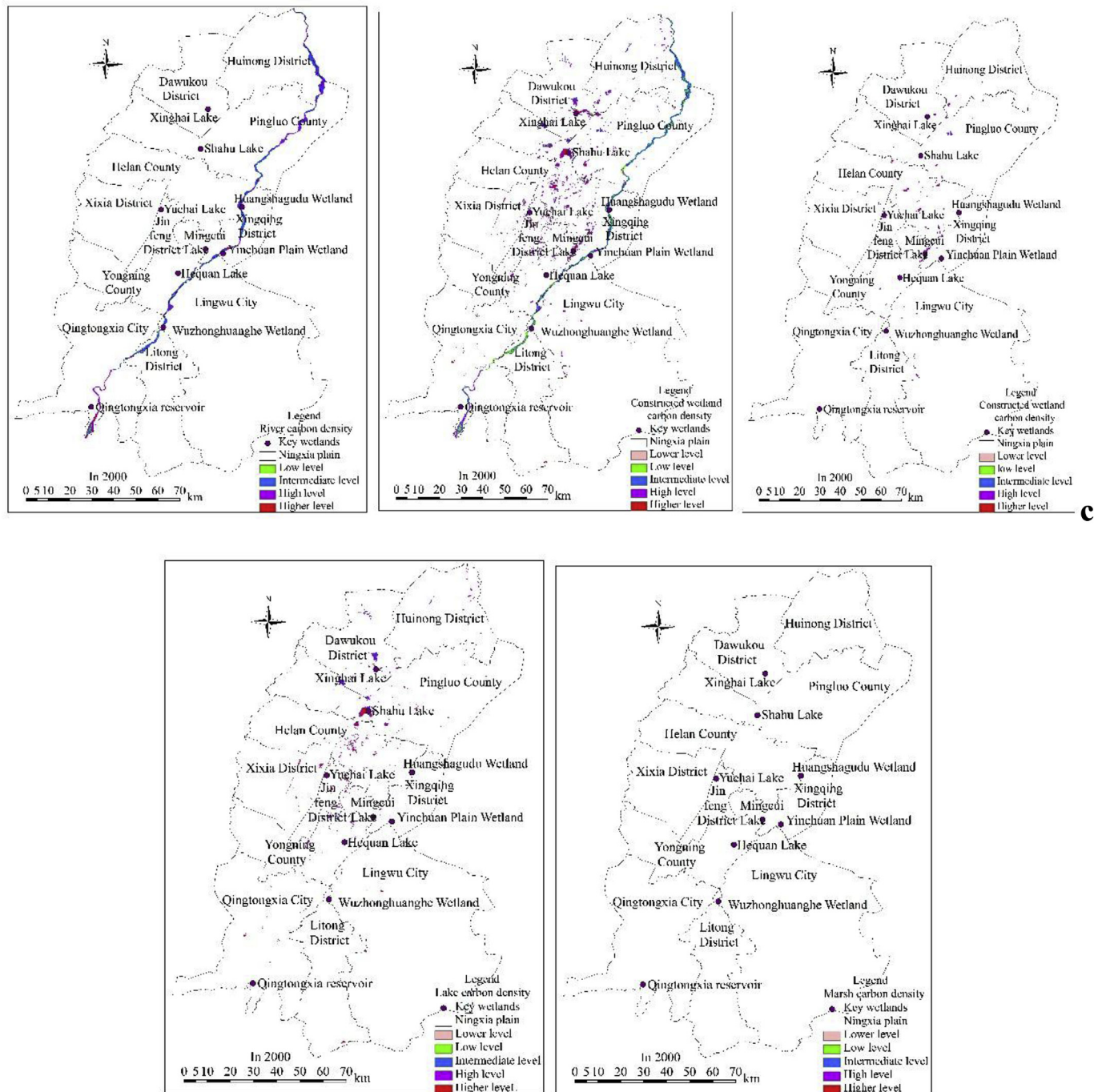


Fig. 4. Spatial distribution of carbon density in Ningxia wetlands in 2000.

$$\Delta C = (C_{t_2} - C_{t_1}) / (t_2 - t_1) \quad (10)$$

Where ΔC is the annual carbon storage change (tCa⁻¹); C_{t_2} is the carbon storage (tC) at time t_2 ; and C_{t_1} is the carbon storage (tC) at time t_1 .

2.2.5. Estimate carbon sinks

Based on the multivariate stepwise regression estimation model (RS-MLRM) and Eqs. (8)–(10) of the four wetland types, vegetation biomass, vegetation carbon storage, and soil carbon storage in the study area, carbon storage and sinks were estimated by using the Band Math module in ENVI in the study wetlands in 2000, 2005, 2010 and 2015. The temporal and spatial changes carbon sinks were analyzed by using ArcGIS in four wetland types in 2000–2015.

2.3. Model implementation using the Ningxia Plain wetland data

2.3.1. Aboveground biomass RS-MLRM

According to international and domestic RS retrieval results of AGB (Harrell et al., 1995; Song et al., 2015; Wei and Tang, 2017; Zhang and Wang, 2011) and based on our study area characteristics, seven vegetation indices were selected: normalized difference vegetation index (NDVI), ratio vegetation index (RVI), difference vegetation index (DVI), modified soil-adjusted vegetation index (MSVI), optimized soil-adjusted vegetation index, soil-adjusted vegetation index (SAVI), and re-normalized difference vegetation index (RDVI). Three principle components (PC1, PC2, and PC3) were used for principle component analysis. Eight textural features were selected: CON (contrast), COR

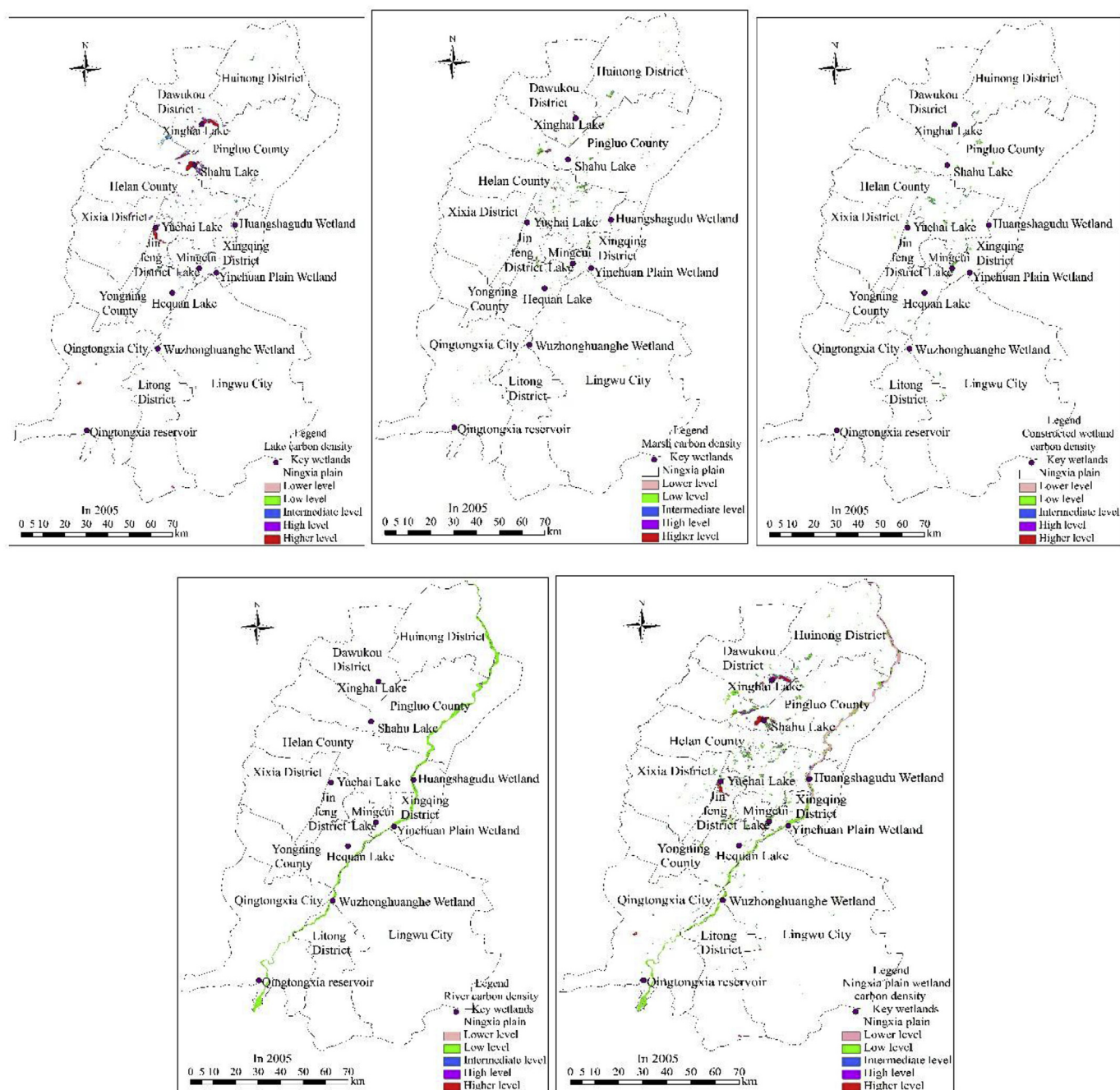


Fig. 5. Spatial distribution of carbon density in Ningxia wetlands in 2005.

(correlation), DIS (dissimilarity), ENT (entropy), HOM (homogeneity), MEAN (mean), ASM (angular second moment), and VAR (variance). Ten soil physical and chemical properties were selected: soil water content, BD, STP, STN, C/N ratio, N/P ratio, and C/P ratio. Three vegetation biomass factors were selected: aboveground biomass (AGB), belowground biomass (BGB), and total biomass (TB).

2.3.2. Belowground biomass RS-MLRM

Pearson correlation analysis was used to analyze the correlation between RS information parameters, AGB and BGB (Fig. 3). Those between soil carbon content, ecological factors, and RS (TM-3, TM-4, and TM-5) were analyzed by multiple stepwise regression with large and significant correlation coefficients. Pearson's correlation analysis revealed significant correlations for AGB with TM-3, TM-4, TM-5, DVI, MSAVI, RDVI, RVI, ME, and EN ($P < 0.05$). There were also significant

correlations ($P < 0.05$) for OLI and TM images with the measured AGB. These results support using RS modeling to evaluate wetland carbon.

2.3.3. Carbon content RS-MLRM

The RS-MLRM values of biomass, VOC, and SOC, such as rivers, lakes, marshes, and constructed wetlands, are shown in Tables 1–3 respectively. The RS-MLRM accuracy of wetland VOC and SOC were analyzed (Tables 4 and 5), and RS-MLRM was found to have a high estimation accuracy and predictive ability. The model significance test, which estimated the wetland carbon sink in the study area, was extremely significant ($P \leq 0.01$). RS factors and vegetation indexes are found to be the main parameters for the inversion of vegetation carbon and SOC in wetlands, and textural features and principal component features may indirectly increase the inversion accuracy. Using Eq. (9),

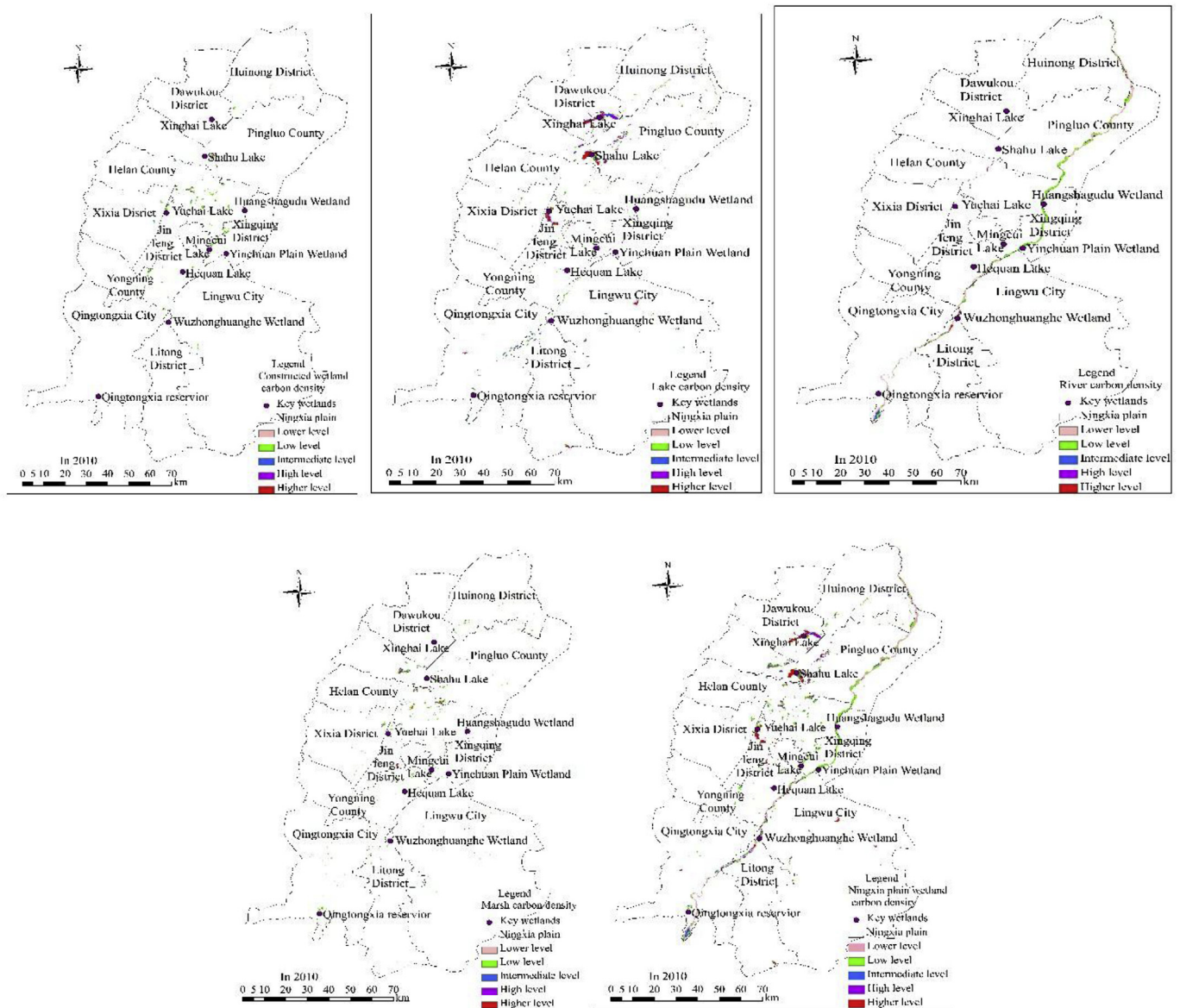


Fig. 6. Spatial distribution of carbon density in Ningxia wetlands in 2010.

the RS-MLRM value of SOC density was obtained for the Ningxia Plain and is shown in Table 6.

3. Results

3.1. Carbon storage and carbon density spatial distribution

Using the RS-MLRM values of wetland carbon content in the Ningxia Plain, thematic maps of carbon density RS estimation were obtained for 2000, 2005, 2010, and 2015. These maps were graded using the natural breakpoint method in ArcGIS, and the percentage of carbon density in each grade was calculated (Figs. 4–8).

The wetland carbon storage is 150.37×10^4 tC (15-year average, the same goes for the values below) in the Ningxia Plain, and the average carbon density was 3924.12 gC/m². The average vegetation and soil carbon stocks are 41.59×10^4 tC and 106.41×10^4 tC, respectively, and the average vegetation and soil carbon densities are 1254.89 gC/m² and 2668.72 gC/m² respectively. Soil carbon stocks were larger than the vegetation carbon stocks. The annual average carbon stocks of rivers, lakes, marshes, and constructed wetlands were 50.03×10^4 tC, 48.40×10^4 tC, 28.41×10^4 tC, and 18.15×10^4 tC,

respectively, and their carbon densities were 31.93 tC/hm², 42.49 tC/hm², 45.02 tC/hm², and 38.92 tC/hm² respectively. The vegetation carbon stocks were 13.86×10^4 tC, 14.27×10^4 tC, 8.40×10^4 tC, and 5.37×10^4 tC, respectively. The soil carbon stocks were 35.41×10^4 tC, 34.13×10^4 tC, 21.87×10^4 tC, and 12.76×10^4 tC, respectively. There were significant differences between the carbon stocks of marshes, rivers, and lakes ($P < 0.05$), but no significant difference between the carbon stocks of rivers and lakes. The average carbon density of the marsh was the highest, and rivers had the highest carbon storage, accounting for 34.43% of the total carbon storage in the Ningxia Plain.

The carbon density of the wetland experienced temporal variability in Ningxia Plain in arid regions. From 2000 to 2005, areas with higher carbon densities tended to decrease, and areas with low carbon sink capacities showed patchy distribution patterns, indicating that wetland carbon density levels were decreasing. From 2010 to 2015, the patchy high carbon density areas increased. River carbon storage levels showed the most significant change, and lake carbon storage levels were relatively stable. The inter-annual variation of carbon storage was larger in the northern wetlands, whereas carbon storage showed smaller changes in the central wetlands. Wetland carbon density were higher in the central and southwestern regions and lower in the

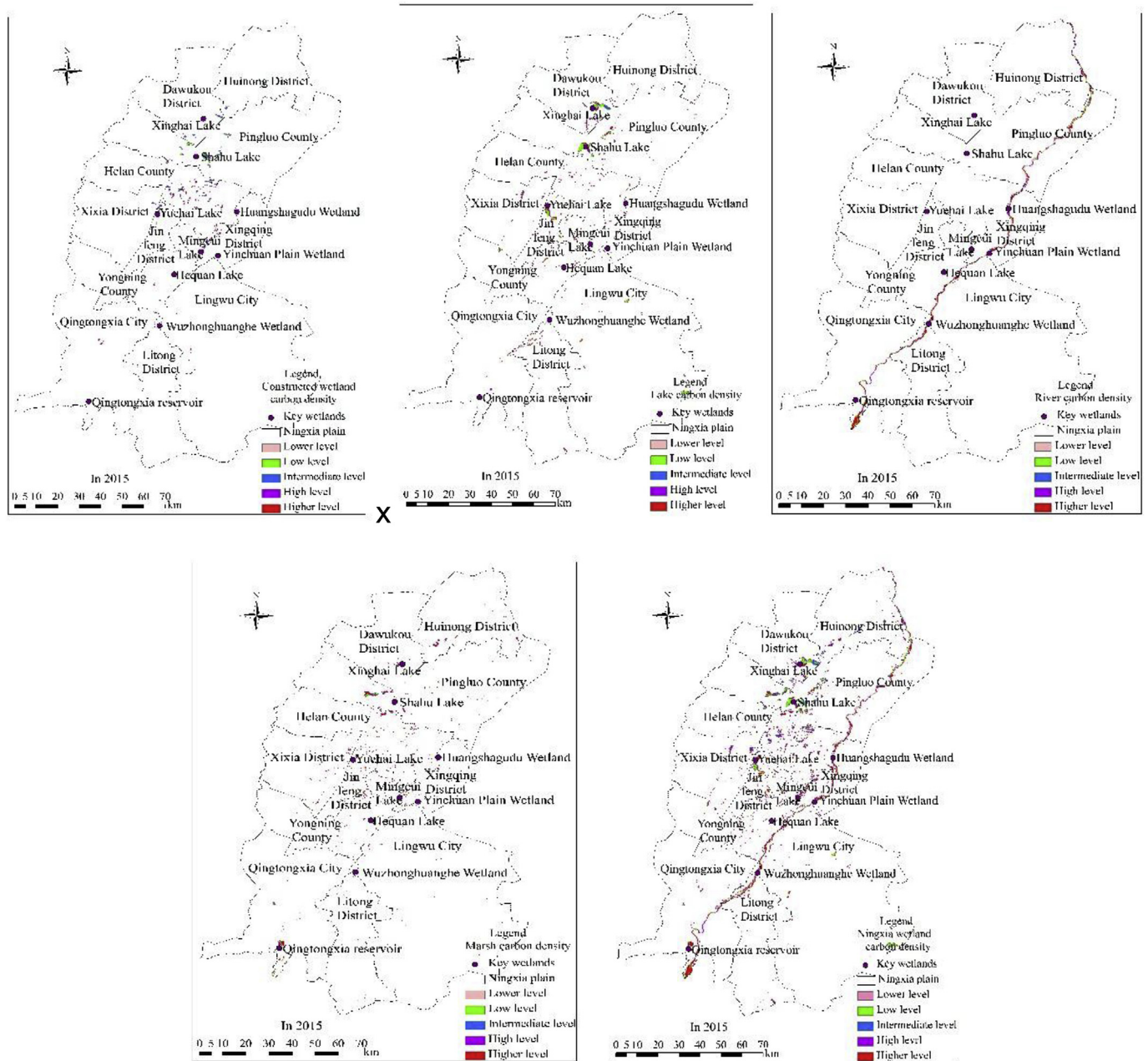


Fig. 7. Spatial distribution of carbon density in Ningxia wetlands in 2015.

northeastern region. The carbon density of wetlands was highest in Pingluo County, with rivers and marshes being the dominant contributors to carbon sinks. Constructed wetlands were the main contributors to carbon sinks in Helan County.

3.2. Carbon storage and carbon density change

The carbon stocks first decreased then increased from 2010 to 2015, increasing by 54.33×10^4 tC in Ningxia Plain wetlands, of which vegetation and soil carbon storage increased by 16.43×10^4 tC and 37.90×10^4 tC, respectively. Of the four wetlands types, marsh carbon storage showed the largest increase, namely 19.14×10^4 tC, and constructed wetland carbon storage increased by 18.34×10^4 tC. From 2000 to 2005, the carbon storage decreased by 36.65×10^4 tC; the reduction of soil carbon storage was larger than that of vegetation, but lake carbon storage increased by 4.79×10^4 tC. From 2005 to 2015, the total carbon storage increased by 90.98×10^4 tC, and river and marsh

carbon storage increased by 29.55×10^4 tC and 28.08×10^4 tC, respectively, which were the major contributors to carbon stocks.

From 2000 to 2015, the wetland carbon density first decreased then increased in the Ningxia Plain (Fig. 9). It was 38.97 t/hm^2 in 2000, dropped to 28.67 t/hm^2 in 2005, increased in 2010, and rose to 49.72 t/hm^2 in 2015. The constructed wetland carbon density increased significantly from 2005 to 2015, indicating that wetland carbon sequestration was significantly enhanced by implementation of the wetland restoration and protection project in Ningxia in 2002.

3.3. Changes in carbon sinks and their spatial distribution

The IPCC-certified terrestrial ecosystem carbon sink refers to the process and quantity of greenhouse gas emission or removal by human activities related to land management, and is based on the principle of conservation of mass related to changes in carbon stocks (Zheng et al., 2013). Carbon sinks were estimated by using the IPCC carbon pool

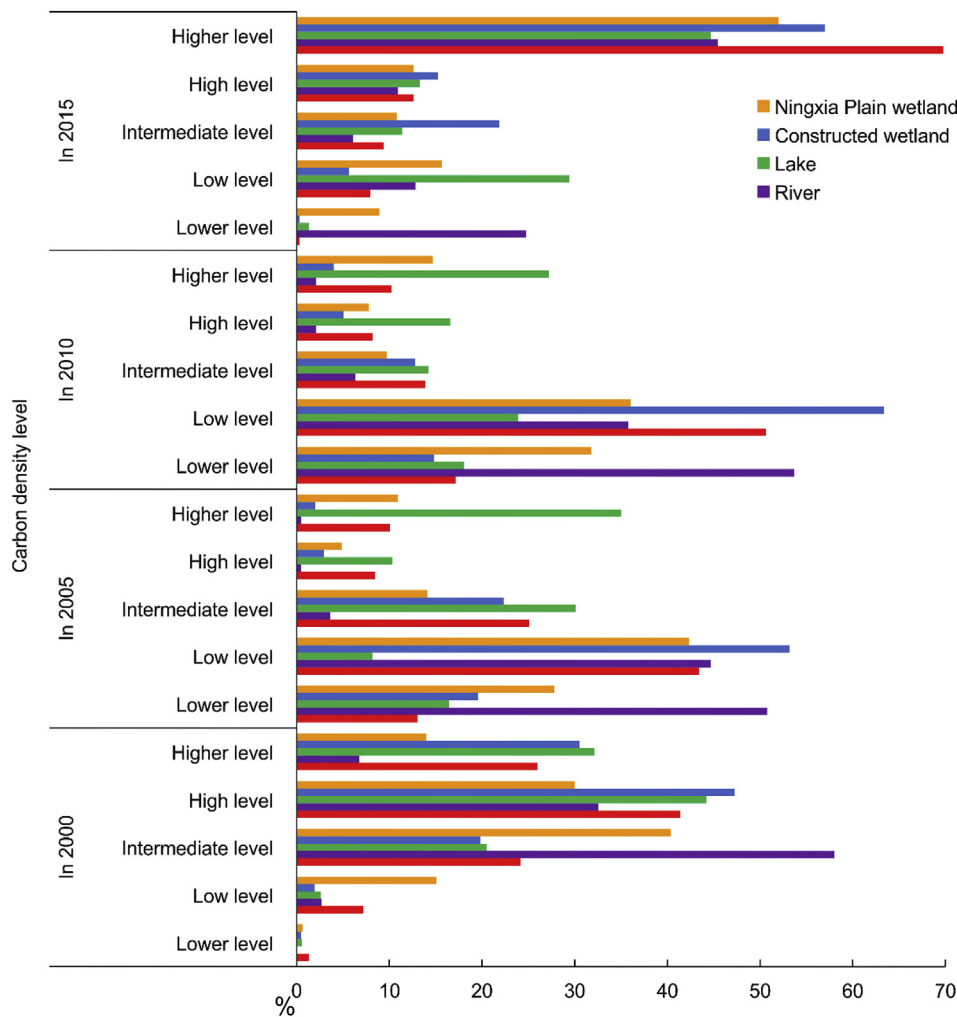


Fig. 8. Distribution of wetland carbon density in the Ningxia Plain from 2000 to 2015.

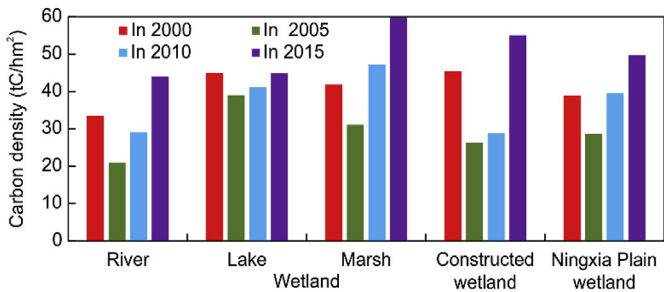


Fig. 9. Wetland carbon density in the Ningxia Plain from 2000 to 2015.

differences carbon sink method in the Ningxia Plain wetland (Fig. 10). Average carbon sequestration was 3.88 tC/a in the Ningxia Plain wetland from 2000 to 2015, but increased again from 2005 to 2015, to which the constructed wetland carbon sink made the largest contribution. Soil carbon sinks were approximately twice as large as vegetation carbon sinks. The contributions of carbon sinks from 2000 to 2015 for the four types of wetlands were ordered as follows: marsh > constructed wetlands > lakes > rivers.

4. Discussion

4.1. Replicability and accuracy of RS-MLRM

RS-MLRM is easily replicable and can be applied to a variety of

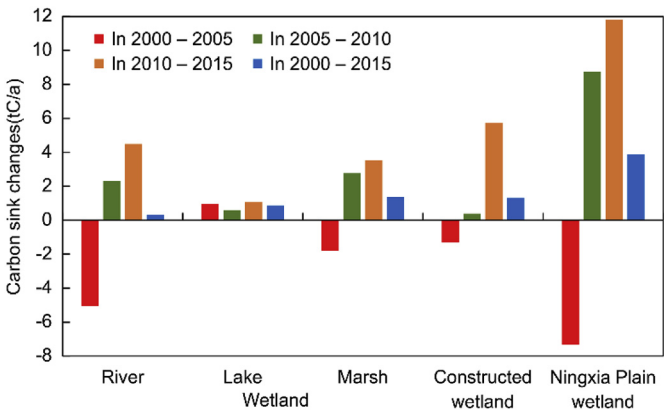


Fig. 10. Evaluation of wetland carbon sinks in the Ningxia Plain based on the IPCC carbon pool-differences method.

Table 7
Comparison of wetland carbon density in different regions.

Region	Carbon density (tC/hm ²)
global (; Yu et al., 2013)	270.17
China (Zheng et al., 2013)	130.91
Ningxia plain (This study)	49.72
Zhangye Heihe wetland (Kong and Zhang, 2015)	45.83

Table 8
Global terrestrial ecosystem vegetation carbon density.

Vegetation types	Area (10 ⁶ km ²)	Total carbon pool (PgC)	Average carbon density (tC/hm ²)
Tropical forest	17.5	340	194.29
Temperate forest	10.4	139	133.65
North forest	13.7	57	41.61
Mediterranean shrubs	2.8	17	60.71
Tropical sparse grassland and grassland	27.6	79	28.62
Temperate grassland	15.0	6	4.00
Desert	27.7	10	3.61
Total	149.3	652	43.67

Note. References: Yu et al., 2013; Chen and Wang (2008).

Table 9
Carbon density of major terrestrial ecosystems in China.

Biomes	Area (10 ⁴ km ²)	Total carbon pool (PgC)	Average carbon density (tC/hm ²)
forest	124.8	75.20	59.78
grassland	33.41	7.04	21.07
Shrubs	178	18.9	10.62
farmland	108	–	–
Total vegetation	736.8	101.1	13.72
Total soil	736.8	58.11	7.89

Note. References: Yu et al., 2013; Zheng et al., 2013; Chen and Wang (2008).

ecosystems. In this study, the inversion results of the RS-MLRM are basically consistent with the results of previous studies.

The RS-MLRM in this study can accurately simulate the organic carbon content, organic carbon density and vegetation biomass of Ningxia Plain wetland in 2015 and historical years (in 2000, in 2005 and in 2010), which was basically consistent with Li Shuang's research results which using a remote sensing factor to construct a biomass inversion model to simulate the status (in 2008) and historical years (in 2006 and in 2004) of vegetation biomass in Honghe Wetland Nature Reserve (Li et al., 2011).

Vegetation biomass, SOC and SOCD were estimated by RS-MLRM and were consistent with the results of previous studies (Bu et al., 2016; Dong et al., 2011, 2015; Mi et al., 2013; Penman et al., 2003; Zhang et al., 2012). In 2000, the SOC of the Ningxia Plain wetland was 4.83 g/kg, which was basically the same as the SOC (6.27 g/kg, including farmland) of the second soil survey in China. In 2010, the SOC of the Ningxia Plain wetland was 4.66 g/kg, which was basically consistent with the 2.48 g/kg of Dong Linlin's research (Dong et al., 2011). The SOC(6.13 g/kg) of the Ningxia Plain wetland is basically consistent with SOC of the Ningxia irrigation area (8.48 g/kg, the range of change is 5.3–15.46 g/kg) studied by Yang Feixia (Yang et al., 2017). The SOC of Shahu (6.46 g/kg) in Pingluo County in 2010 is close to the SOC of farmland in Pingluo County in Ningxia Plain (8.67 g/kg) studied by Li Xiaoxiao (Li, 2013). The SOCD (2.63 kg/m²) of Ningxia Plain wetland in 2000 was close to the SOCD (1.66 g/kg) in China's second soil survey. The SOCD of Ningxia Plain wetland (2.74 kg/m²) in 2010 was basically

Table 10
SOC, TN, TP and C/N, C/P, N/P, and environmental factors correlation analysis.

Index	SOC	TN	TP	pH	Water content of soil (%)	Salinity (g/kg)	Soil bulk density (g/cm ³)
SOC	1	0.841**	0.199	−0.832	0.831**	−0.347	−0.615*
TN		1	0.502*	−0.325*	0.712*	−0.056	−0.043
TP			1	0.032	0.629*	−0.278**	−0.272
C/N	0.549*	0.682*	−0.712*	−0.438	0.573*	0.387*	0.484
C/P	0.674*	0.802*	0.106	−0.277	0.677*	0.297*	−0.487
N/P	0.481	0.699*	0.129	0.122	0.334	0.359	−0.006

*Correlation is significant at 0.05 probability level, **Correlation is significant at 0.01 probability level.

consistent with the SOCD of 2.12 kg/m² in the Ningxia Yellow River Irrigation District. The SOCD (2.30 kg/m²) in Shahu, Pingluo County in Ningxia Plain, and the SOCD (2.33 kg/m²) in Pingluo County, which is studied by Li Xiaoxiao (Li, 2013).

The vegetation biomass of Mingcui Lake in Ningxia Plain in 2000 was 2.06 kg/m², which was close to the Phragmites australis biomass of Yinchuan Plain wetland (2.46 kg/m²) studied by Zhang Yufeng at (Zhang et al., 2012). In 2015, the vegetation biomass of lake wetland in Ningxia Plain was 3.65 kg/m², which was basically consistent with the biomass (3.44 kg/m²) in the Yinchuan Plain wetland studied by Qiao Bin (Qiao et al., 2017). In 2015, the biomass of wetland vegetation in the Ningxia Plain was 4.05 kg/m², which was close to the Yinchuan Plain wetland Phragmites australis biomass (3.37 kg/m²) studied by Zhao Yongquan (Zhao, 2014). This indicating that the inclusion of textural factors in RS-MLRM development improves model accuracy. The accuracy of wetland carbon sink estimation can be improved through multi-source data fusion and model parameter selection and can be estimated in the historical year. The accuracy of the model predictions was high, and it is proposed that the models themselves could be broadly applied to other similar wetland ecosystems.

Further, the estimation models of organic carbon RS developed for each of the four wetland types (river, lake, marsh, and constructed were distinct, so that differences in the formation of vegetation cover and soil were accounted for, making the methodology broadly applicable and, to a certain extent, universal. The model construction can therefore potentially be applied to a variety of ecosystems.

4.2. High carbon storage function of wetland in Ningxia Plain

The average carbon density was higher in the Ningxia Plain wetland in the arid regions than in inland arid regions of northwest China (Kong and Zhang, 2015) (Table 7). The vegetation carbon density was between that of temperate grassland biota (4 tC/hm²) and tropical sparse steppe and grassland biota (28.62 tC/hm²) (Chen and Wang, 2008) (Table 8). In 2015, the carbon density in the Ningxia Plain wetland was higher than that in northern forests in China (41.61 tC/hm²) (Yu et al., 2013). The marsh carbon density was similar to that of Mediterranean shrubs (60.71 tC/hm²) (Chen and Wang, 2008), and close to the average carbon density of China's forest ecosystems (59.78 tC/hm²) (Chen and Wang, 2008) (Table 9). The vegetation carbon density in the Ningxia Plain wetland (from 2000 to 2015) was higher than the average carbon density of wetland in China (13.72 tC/hm²) (Zheng et al., 2013), which further shows that the carbon sink of wetland in the Ningxia Plain is significant, and that wetland restoration and protection have had remarkably positive effects. The results indicate that the ecosystem restoration project that initiated in the region in 2002 has been effective at restoring a healthy wetland habitat.

4.3. Environmental factors affecting wetland carbon sinks

The various environmental factors that make up an ecosystem were interrelated and interacting, and affect changes of organic carbon in a region (Liu, 2004; Meng et al., 2011). Compared to seasonal rivers in the inland arid regions in Northwest China, the arid region in Ningxia

Plain exhibits relatively small changes in water volume and can continuously supply the water required by wetlands. On the other hand, since 2002, the local government has implemented a series of wetland restoration and protection projects in the Ningxia to increase the wetland area and significantly increase the vegetation cover and carbon sequestration effect.

Climatic factors have a significant impact on CO₂ and wetland area (Liu, 2013; Lei et al., 2016). For example, with rising temperatures, wetland evaporation increases, leading to an increase in the wetland water demand and causing changes in wetland biomass and vegetation cover. Increased precipitation lead to temperature and biomass changes and a decrease in wetland water demand. In the Ningxia Plain, average annual precipitation and temperature were relatively low, the decomposition rate of soil organic matter is slow, and organic matter accumulates; thus, the carbon density is higher.

The accumulation of wetland organic carbon depends largely on the quantity and distribution of plant material inputs. Biomass is the decisive factor affecting the carbon content of the soil surface (Liu, 2013). The formation of river soil is constantly affected by scouring of the semi-arid regions, and riverbed vegetation roots were underdeveloped, with low biomass, resulting in less accumulation of soil carbon and lower carbon density. The dominant species in the marsh are reeds, with a cover of over 90%. Reed marsh is a high-carbon input and low-carbon output plant with high productivity and whose litter is completely returned to the soil. Wetland soils are often saturated with water, which inhibits the decomposition of organic matter. On the other hand, deposition of a large amount of aquatic plant residue may also lead to high carbon density in marshes (Meng et al., 2011). Therefore, marshes have a greater carbon sink capacity than lakes and rivers do.

Water conditions, especially changes in water level, are often the decisive factors affecting the migration, transformation, and accumulation of elements. The accumulation of wetland organic carbon further depends on the balance between production and decomposition, and the major factor affecting the accumulation of organic carbon is the speed of organic matter decomposition (Song et al., 2011). The content of organic carbon in the marsh surface soil layer (0–40 cm) was higher than that of the other three wetlands. Since the marsh is located in a seasonal flooding zone, the soil moisture is often saturated or super-saturated, and the anaerobic reduction conditions inhibit the decomposition of organic matter, and this, along with higher vegetation cover, is conducive to the accumulation of organic carbon (Zheng et al., 2013).

In some river floodplains and terraces, the soil is often sprayed with water. However, frequent flooding during wet seasons has allowed the wetlands to sustain flooding for a longer period of time (Liu, 2013). Intense flooding and the consequent dense vegetation cover result in large amounts of root exudates and secretions and rich SOC. The soil is inundated with less water at some of the lake edges. Thus, strong oxidation conditions promote the action of soil microorganisms during the oxygen decomposition of organic matter. Combined with greater human interference and fewer plant residues, lake make a conducive environment for the accumulation of organic carbon.

Physical and chemical properties and nutrients in wetland are important constraints of wetland organic matter decomposition processes, affecting wetland ecosystem carbon sequestration potential (Liu, 2013). Significant positive correlation were observed between SOC and soil water content ($P < 0.05$) as well as a SOC and STN ($P < 0.01$). SOC had a significant correlation with soil C/N and C/P ($P < 0.05$), which indicates that STN, and soil C/N, and soil C/P had a significant effect on SOC. A negative correlation was observed between SOC and soil BD ($P < 0.05$), indicating a higher BD and lower SOC, which is consistent with the findings previous research (Bu et al., 2016; Meng et al., 2011; Zheng et al., 2013). SOC did not show a significant correlation with soil salinity, STP, or pH (Table 10).

5. Conclusions

- (1) By analyzing correlations between multiple RS factors and measured VOC and SOC, the established optimal RS-MLRM could estimate carbon sinks in the Ningxia Plain wetlands with high accuracy and predictability. The RS-MLRM method also has a certain degree of universality
- (2) Wetland carbon density increased significantly wetlands of the Ningxia Plain in the arid regions from 2000 to 2015. The carbon sink effect was significant, and wetland restoration and protection efforts had a significant effect on improving carbon sequestration. Soil carbon sequestration was approximately twice that of vegetation. The constructed wetland carbon sink had the largest capacity, indicating that positive human intervention on wetlands enhanced the carbon sink effect.
- (3) Human activities, policy factors, wetland soil physical and chemical properties and nutrients, are the main factors affecting carbon sequestration in the Ningxia Plain wetland in the arid regions. Climate and vegetation biomass were also important factors that affect carbon sequestration.
- (4) Encouraging reasonable human intervention to restore and protect wetland ecosystems in arid regions will not only enhance wetland biological primary productivity and ecological functions but also improve the surrounding climate conditions and natural landscapes. The improved living environment would further promote the development of ecological sustainable civilization.

Declaration of interest statement

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.atmosenv.2019.02.019>.

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